

ON THE PROGENITOR SYSTEM OF THE TYPE Iax SUPERNOVA 2014dt IN M61

RYAN J. FOLEY^{1,2}, SCHUYLER D. VAN DYK³, SAURABH W. JHA⁴, KELSEY I. CLUBB⁵, ALEXEI V. FILIPPENKO⁵,
JON C. MAUERHAN⁵, ADAM A. MILLER^{6,7,†}, AND NATHAN SMITH⁸*Draft version December 4, 2014*

ABSTRACT

We present pre-explosion and post-explosion *Hubble Space Telescope* images of the Type Iax supernova (SN Iax) 2014dt in M61. After astrometrically aligning these images, we do not detect any stellar sources at the position of the SN in the pre-explosion images to relatively deep limits (3σ limits of $M_{F438W} > -5.0$ mag and $M_{F814W} > -5.9$ mag). These limits are similar to the luminosity of SN 2012Z's progenitor system ($M_{F435W} = -5.43 \pm 0.15$ and $M_{F814W} = -5.24 \pm 0.16$ mag), the only probable detected progenitor system in pre-explosion images of a SN Iax, and indeed, of any white dwarf supernova. SN 2014dt is consistent with having a C/O white-dwarf primary/helium-star companion progenitor system, as was suggested for SN 2012Z, although perhaps with a slightly smaller or hotter donor. The data are also consistent with SN 2014dt having a low-mass red giant or main-sequence star companion. The data rule out main-sequence stars with $M_{\text{init}} \gtrsim 16M_{\odot}$ and most evolved stars with $M_{\text{init}} \gtrsim 8M_{\odot}$ as being the progenitor of SN 2014dt. Hot Wolf-Rayet stars are also allowed, but the lack of nearby bright sources makes this scenario unlikely. Because of its proximity ($D = 12$ Mpc), SN 2014dt is ideal for long-term monitoring, where images in ~ 2 years may detect the companion star or the luminous bound remnant of the progenitor white dwarf.

Subject headings: galaxies—individual(M61), supernovae—general, supernovae—individual (SN 2014dt)

1. INTRODUCTION

Type Iax supernovae (SNe Iax) are a recently defined class of stellar explosion (Foley et al. 2013, hereafter F13). They are, in many ways, observationally similar to SNe Ia, having comparable spectra and thus compositions (e.g., Li et al. 2003; Branch et al. 2005; Chornock et al. 2006; Jha et al. 2006; Foley et al. 2009, 2010a). However, SNe Iax are less energetic, with ejecta velocities near maximum light 20–80% that of typical SNe Ia (e.g., Narayan et al. 2011; F13; White et al. 2014). SNe Iax also tend to have lower luminosity than SNe Ia (e.g., McClelland et al. 2010; Stritzinger et al. 2014a,b), further indicating a low-energy explosion.

One important difference between SNe Iax and SNe Ia is that we have imaged the probable progenitor system of a SN Iax (McCully et al. 2014a, hereafter, M14a), while no progenitor system of a SN Ia has yet been directly observed. For SN 2012Z, M14a detected a luminous, blue source in pre-explosion *Hubble Space Telescope* (*HST*)

images at the SN position. Their favored interpretation is that this source is the nondegenerate He companion star to a C/O white dwarf (WD), as originally predicted by F13 as the likely progenitor scenario for SNe Iax. However, it is also possible that the light came from a massive star that exploded to cause SN 2012Z or an accretion disk around the exploding WD.

An important prediction from both simple energetic arguments (Foley 2008; Foley et al. 2009, 2013; McCully et al. 2014b) or from detailed explosion models (Jordan et al. 2012; Kromer et al. 2013; Fink et al. 2014) is that at least some of the time, a SN Iax, if coming from a C/O WD, should leave behind a bound remnant star. Since the remnant retains a significant amount of radioactive material after the explosion (Kromer et al. 2013), this star will likely become quite luminous on the timescale of years to decades (Bildsten et al., in preparation).

Using *HST* images that include the location of SN 2008ha, a low-luminosity SN Iax (Foley et al. 2009, 2010a; Valenti et al. 2009), from 4 years after the explosion, Foley et al. (2014) detected a luminous, red source at the position of the SN. Since these images came after the explosion, the source could be a thermally pulsating asymptotic giant branch (TP-AGB) companion star or a bound remnant star. If the sources detected at the positions of SNe 2008ha and 2012Z are both companion stars, SNe Iax must have a diverse set of progenitor systems.

Until recently, SN 2008ge was the only other SN Iax with pre-explosion *HST* imaging (Foley et al. 2010b). These data are not particularly deep (3σ limit of $M_V > -6.9$ mag), but rule out particularly massive stars as potential progenitors. Notably, SN 2008ge occurred in an S0 galaxy with no star formation to deep limits (Foley et al. 2010b), which indirectly disfavors a massive star progenitor.

¹ Astronomy Department, University of Illinois at Urbana-Champaign, 1002 W. Green Street, Urbana, IL 61801, USA

² Department of Physics, University of Illinois Urbana-Champaign, 1110 W. Green Street, Urbana, IL 61801, USA

³ IPAC/Caltech, Mail Code 100-22, Pasadena, CA 91125, USA

⁴ Department of Physics and Astronomy, Rutgers, The State University of New Jersey, 136 Frelinghuysen Road, Piscataway, NJ 08854, USA

⁵ Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA

⁶ Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, MS 169-506, Pasadena, CA 91109, USA

⁷ California Institute of Technology, Pasadena, CA 91125, USA

⁸ Steward Observatory, University of Arizona, Tucson, AZ 85721, USA

[†] Hubble Fellow

In this *Letter*, we present deep pre- and post-explosion *HST* images of SN 2014dt, a SN Iax discovered in M61 at a distance of only 12.3 Mpc. By comparing the pre- and post-explosion images, we precisely determine the position of the SN in the pre-explosion images. We do not detect any star at that position with a 3σ limit of $M_{F450W} > -5.0$ mag.

2. OBSERVATIONS AND DATA REDUCTION

SN 2014dt was detected in M61 on 2014 October 29.8 (all times are UT) at 13.6 mag by Nakano & Itagaki (2014) and promptly classified as a SN Iax by Ochner et al. (2014) from a spectrum obtained 2014 October 31.2. The SN was past peak at discovery and there are no recent nondetections which constrain the date of explosion.

M61 is in the Virgo cluster and has a distance of 12.3 Mpc ($\mu = 30.45 \pm 0.10$ mag) as determined by with the expanding photosphere method (EPM) applied to SN 2008in, also in M61 (Bose & Kumar 2014). This is consistent with the Tully-Fisher distance of 11.0 Mpc ($\mu = 30.21 \pm 0.70$ mag; Schoeniger & Sofue 1997), and the redshift-derived distance (corrected for Virgo infall) of 13.1 Mpc (30.59 ± 0.16 mag). Here we assume the EPM distance modulus, but increase the uncertainty to 0.24 mag, corresponding to the offset between the EPM and Tully-Fisher measurements; this range also includes the redshift-derived distance.

On 18.6 November 2014, we obtained a low-resolution spectrum of SN 2014dt with the Kast double spectrograph (Miller & Stone 1993) on the Shane 3 m telescope at Lick Observatory. Standard CCD processing and spectrum extraction were accomplished with IRAF¹⁰. The data were extracted using the optimal algorithm of Horne (1986). Low-order polynomial fits to calibration-lamp spectra were used to establish the wavelength scale, and small adjustments derived from night-sky lines in the object frames were applied. We employed our own IDL routines to flux calibrate the data and remove telluric lines using the well-exposed continua of spectrophotometric standards (Wade & Horne 1988; Foley et al. 2003; Silverman et al. 2012). The spectrum is presented in Figure 1.

The position of SN 2014dt was imaged by *HST*/WFPC2 on 2001 July 27.10 (Program GO-9042; PI Smartt) in F450W (roughly *B*) and F814W (roughly *I*), each for 460 s. We obtained drizzled mosaics from the Hubble Legacy Archive.

We also imaged SN 2014dt with *HST*/WFC3/UVIS in F438W (roughly *B* and well matched to the pre-explosion F450W image) on 2014 November 18.89 (Program GO-13683; PI Van Dyk). We took 20 short (20 s) exposures so as to not saturate the SN.

We combined exposures (including cosmic ray rejection) using AstroDrizzle. We drizzled the images to the native scale of WFC3, $0''.04$ pixel⁻¹. We also ran the individual fit images of the SN through Dolphot, an extension of HSTPhot (Dolphin 2000), and measured the brightness to be $m_{F438W} = 16.483 \pm 0.001$ mag.

¹⁰ IRAF: the Image Reduction and Analysis Facility is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation (NSF).

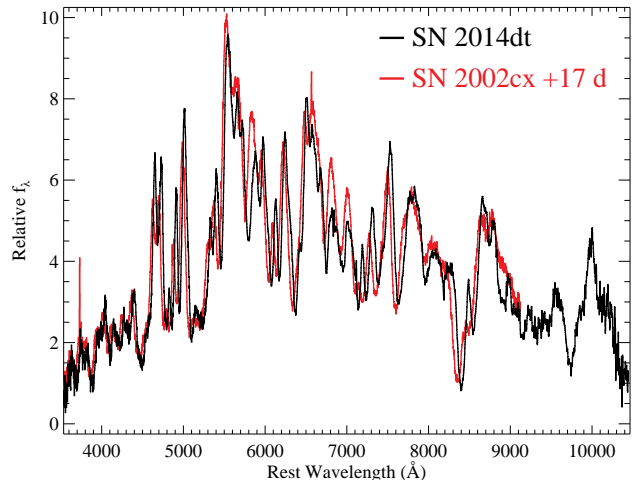


FIG. 1.— Optical spectrum of SN 2014dt (black) compared to that of SN 2002cx at +17 d (red).

Using 30 stars in common between the F450W pre-explosion and F438W post-explosion images, we computed a relative astrometric solution between the two images and precisely determined the position of SN 2014dt in the pre-explosion image. The position of SN 2014dt has uncertainties of 0.13 and 0.10 pixels ($0''.006$ and $0''.005$) in the horizontal and vertical directions, respectively. After the initial astrometric match, we are able to transform between the two pre-explosion images with negligible additional positional uncertainty.

Pre- and post-explosion images of SN 2014dt and its surrounding environment are shown in Figure 2.

We conducted Dolphot point-spread function photometry on the individual pre-explosion *HST* fit frames, using the suggested Dolphot parameters for WFPC2. We only consider photometry with a “flag” of 0 and an “object type” of 1 (point sources) in our results.

There is no source detected at the position of SN 2014dt in either pre-explosion image. The closest source, detected by Dolphot at 3.6σ with 25.61 mag in F450W only, is $1''.64$ (97 pc) to the southwest of the SN position. The next closest, detected at 3.6σ with 24.60 mag in F814W only, is $3''.21$ (190 pc) to the southeast. The closest source detected in both bands (with 24.06 mag, 11.6σ at F450W; 23.47 mag, 9.4σ at F814W) is $3''.59$ (210 pc) to the northeast. The 3σ limiting magnitude corresponds to $m_{F450W} > 25.7$ and $m_{F814W} > 24.8$ mag, respectively.

3. ANALYSIS

SN 2014dt is spectroscopically a SN Iax. The spectrum presented in Figure 1 is compared to one of SN 2002cx, the prototypical member of the class (Filippenko 2003; Li et al. 2003), at 17 days after maximum brightness. They are nearly identical except SN 2014dt appears to have a slightly lower ejecta velocity. Importantly, there is no indication of hydrogen in the spectrum.

At $D = 12.3$ Mpc, SN 2014dt had $M \approx -17.1$ mag at discovery. Using standard SN Iax light curves (F13), SN 2014dt likely peaked at $M \approx -18$ mag, also consistent with other SNe Iax.

Although it is difficult to measure host-galaxy reddening,

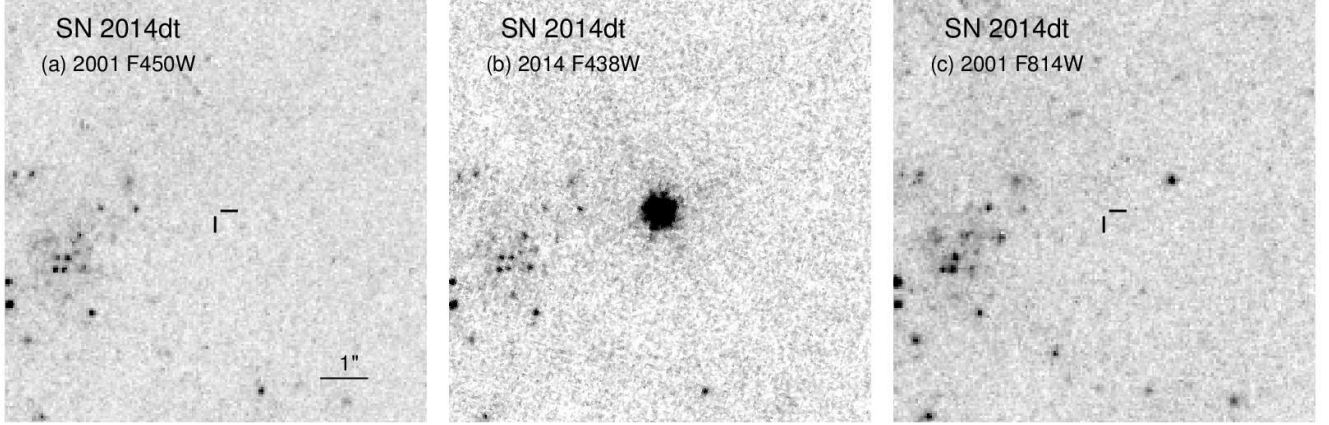


FIG. 2.— *HST*/WFC3 F438W image of SN 2014dt (b) and its surrounding environment. Aligned pre-explosion *HST*/WFPC2 F450W (a) and F814W (c) PC1-chip images are also shown to the same scale. The position of SN 2014dt in the pre-explosion images is marked. No star is detected at the SN location in either pre-explosion image.

ing from SN Iax colors (F13), SN 2014dt does not appear to have any host-galaxy reddening. The SN has a reasonably blue continuum and there is no Na D absorption in our high signal-to-noise ratio low-resolution spectrum. This is consistent with the expected reddening from a relatively clean part of a face-on spiral galaxy.

No sources were detected at the position of SN 2014dt in pre-explosion *HST* images. With our given distance modulus ($\mu = 30.45$ mag), and our Milky Way and host-galaxy reddening estimates ($E(B-V) = 0.02$ and 0 mag, respectively), the 3σ limits correspond to $M_{F450W} > -5.0$ and $M_{F814} > -5.9$ mag. These limits, converted into blackbody temperature and F814W luminosity limits, are presented in Figure 3. They are similar to the observed brightness of the probable SN 2012Z progenitor system ($M_{F435W} = -5.43 \pm 0.15$ and $M_{F814W} = -5.24 \pm 0.16$ mag). Formally, the SN 2014dt limits are 0.40 mag deeper than the SN 2012Z progenitor system detection in F435W/F450W. However, this is only 1.4σ different when including uncertainties in the SN 2012Z progenitor system photometry and the distance to M61. We therefore cannot rule out a progenitor system for SN 2014dt that is similar to that of SN 2012Z.

Our limits are not quite deep enough to rule out a progenitor system similar to that of the source coincident with SN 2008ha at late times ($M_{F814W} = -5.42 \pm 0.22$ mag). Moreover, a system similar to that of V445 Pup (the only known He nova; Kato & Hachisu 2003), thought to be a C/O WD with a He-star companion (Kato et al. 2008; Woudt et al. 2009), would be barely undetected in the pre-explosion images. Therefore, SN 2014dt could have a progenitor system similar to any of these comparison objects.

Nonetheless, a large number of potential progenitor systems have been excluded. Using a projected offset of 2.3 kpc, and a metallicity map of M61 (Pilyugin et al. 2014), we find a metallicity at the SN position of $12 + \log(\text{O}/\text{H}) = 8.68$, which on the scale adopted by Pilyugin et al. (2014) is roughly 1.5 times solar. From single-star evolutionary models at this metallicity (Bertelli et al. 2009), the pre-explosion limits are inconsistent with systems containing a red giant (RG) or horizontal branch (HB) star with $M_{\text{init}} \gtrsim 8 M_{\odot}$ or main-sequence stars with $M_{\text{init}} \gtrsim 16 M_{\odot}$. Of course,

these kinds of stars are unlikely to have been the progenitor because of the lack of hydrogen in the SN spectrum; nonetheless, these limits apply to companion stars as well.

The data do not exclude very hot Wolf-Rayet stars, which can be relatively faint at optical wavelengths (Shara et al. 2013). However, Wolf-Rayet stars would likely be physically close to other massive stars. SN 2014dt exploded in a region that is ~ 100 pc from any detected sources and $\gtrsim 200$ pc from any particularly bright sources, making the Wolf-Rayet scenario less likely.

4. DISCUSSION AND CONCLUSIONS

Using *HST* images obtained 13 years before SN 2014dt, a clear SN Iax, we place limits on its progenitor system. This is the third SN Iax with pre-explosion *HST* images and the second deepest (after SN 2012Z).

With these data, we are able to exclude many massive stars as progenitors for SN 2014dt. Specifically, main-sequence stars with $M_{\text{init}} \gtrsim 16 M_{\odot}$ and RG/HB stars with $M_{\text{init}} \gtrsim 8 M_{\odot}$ are excluded. Some Wolf-Rayet stars are still allowed, but the lack of bright nearby stars make a Wolf-Rayet progenitor unlikely.

If the progenitor system of SN 2012Z were in M61, we would perhaps marginally detect it. Since we did not detect any sources at the position of SN 2014dt, its progenitor system was likely fainter (in *B*) than that of SN 2012Z.

Many of the He stars in the He-star-C/O-WD progenitor models of Liu et al. (2010) have roughly the same luminosity but varying temperature. Since the He-star spectral energy distribution peaks in the ultraviolet, the effective temperature dictates the brightness in the *HST* bands. A large region of the He-star parameter space is still allowed by the current data. However, future data, particularly at shorter UV wavelengths, should be able to place strong constraints on the existence of such a star.

The pre-explosion data also do not exclude a red giant star similar to what may be the companion of SN 2008ha, although the data are within ~ 0.5 mag of being able to detect such a star. Again, future data should be able to easily detect a similar star, although as to the case of SN 2008ha, the interpretation of such a detection would

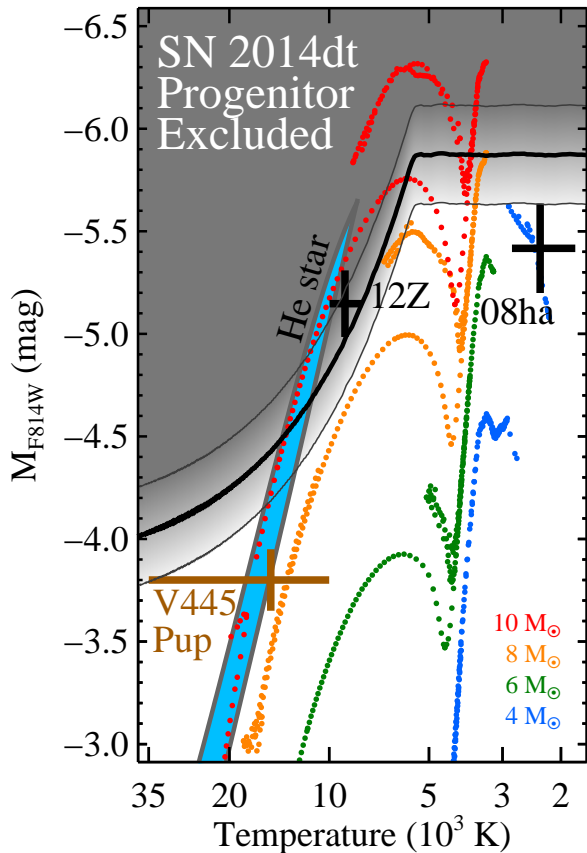


FIG. 3.— Hertzsprung-Russell diagram for SN Iax progenitor systems. SN 2014dt is not detected, and the region of the H-R diagram excluded is shaded dark gray. The allowed region is white. The black curve represents the single-band 3σ limits for black body sources. The gray gradient band indicates the additional 1σ distance-modulus uncertainty. The white region is allowed for the progenitor system. The SN 2012Z progenitor system (black cross; M14a) and the V445 Pup progenitor system (brown cross; F814W magnitude estimated from temperature and V-band magnitude; Woudt et al. 2009) are shown. The source coincident with SN 2008ha in post-explosion images is also marked with a black cross. This source may be the companion star or the bound remnant star (Foley et al. 2014). Also plotted are stellar evolution tracks for stars with initial masses of 4, 6, 8, and 10 M_{\odot} (Bertelli et al. 2009) and the region predicted for one set of He-star progenitor models from Liu et al. (2010, blue region).

be somewhat ambiguous.

There are now three SNe Iax with reasonably deep pre-explosion images. A probable luminous blue progenitor system was detected for SN 2012Z (M14a), the SN

with the deepest pre-explosion data, while no progenitor was detected for either SN 2008ge (Foley et al. 2010b) or 2014dt. Foley et al. (2014) detected a luminous red source coincident with SN 2008ha 4 years after the explosion that could be a companion star or the bound remnant of the progenitor WD. These four SNe independently and jointly rule out massive stars as SN Iax progenitors.

SN 2014dt, being at $D = 12.3$ Mpc, is likely the closest SN Iax yet discovered (SN 2010ae was at 12.9 Mpc; Stritzinger et al. 2014a), making it a great candidate for long-term monitoring. Of the 5 SNe Iax discovered within ~ 20 Mpc (SNe 2008ge, 2008ha, 2010ae, 2010el, and 2014dt), SN 2014dt is the best SN for such observations; SNe 2010ae and 2010el have significant reddening, SN 2008ge was close to a bright galactic nucleus, and SN 2008ha was the faintest and most distant. SNe Iax fade by ~ 12 mag in the first two years (McCully et al. 2014b). SN 2014dt peaked at $M \approx -18$ mag, and will be roughly as bright as the pre-explosion image limits in two years. Around that time, deep images may be able to detect emission from either a companion star or the WD remnant.

Facility: Hubble Space Telescope (WFPC2, WFC3), Lick Shane (Kast)

Based on observations made with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute (STScI), which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with and funded through program GO-13683. Data were obtained through the Hubble Legacy Archive, which is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESA) and the Canadian Astronomy Data Centre (CADC/NRC/CSA).

SN Iax research at the University of Illinois is supported in part through NASA/*HST* grant GO-12999.01. This research at Rutgers University was supported through NASA/*HST* grant GO-12913.01 and National Science Foundation (NSF) CAREER award AST-0847157 to S.W.J. A.A.M. acknowledges support for this work by NASA from Hubble Fellowship grant HST-HF-51325.01, awarded by STScI. A.V.F.'s group at U.C. Berkeley is supported by the Christopher R. Redlich Fund, the TABASGO Foundation, and NSF grant AST-1211916.

REFERENCES

- Bertelli, G., Nasi, E., Girardi, L., & Marigo, P. 2009, *A&A*, 508, 355
- Bose, S., & Kumar, B. 2014, *ApJ*, 782, 98
- Branch, D., Baron, E., Hall, N., Melakayil, M., & Parrent, J. 2005, *PASP*, 117, 545
- Chornock, R., Filippenko, A. V., Branch, D., Foley, R. J., Jha, S., & Li, W. 2006, *PASP*, 118, 722
- Dolphin, A. E. 2000, *PASP*, 112, 1383
- Filippenko, A. V. 2003, in *From Twilight to Highlight: The Physics of Supernovae*, ed. W. Hillebrandt & B. Leibundgut, 171
- Fink, M., et al. 2014, *MNRAS*, 438, 1762
- Foley, R. J. 2008, *Central Bureau Electronic Telegrams*, 1576, 2
- Foley, R. J., Brown, P. J., Rest, A., Challis, P. J., Kirshner, R. P., & Wood-Vasey, W. M. 2010a, *ApJ*, 708, L61
- Foley, R. J., et al. 2013, *ApJ*, 767, 57
- . 2009, *AJ*, 138, 376
- Foley, R. J., McCully, C., Jha, S. W., Bildsten, L., Fong, W.-f., Narayan, G., Rest, A., & Stritzinger, M. D. 2014, *ApJ*, 792, 29
- Foley, R. J., et al. 2003, *PASP*, 115, 1220
- . 2010b, *AJ*, 140, 1321
- Horne, K. 1986, *PASP*, 98, 609
- Jha, S., Branch, D., Chornock, R., Foley, R. J., Li, W., Swift, B. J., Casebeer, D., & Filippenko, A. V. 2006, *AJ*, 132, 189

- Jordan, IV, G. C., Perets, H. B., Fisher, R. T., & van Rossum, D. R. 2012, *ApJ*, 761, L23 [\[\]](#)
- Kato, M., & Hachisu, I. 2003, *ApJ*, 598, L107 [\[\]](#)
- Kato, M., Hachisu, I., Kiyota, S., & Saio, H. 2008, *ApJ*, 684, 1366 [\[\]](#)
- Kromer, M., et al. 2013, *MNRAS*, 429, 2287 [\[\]](#)
- Li, W., et al. 2003, *PASP*, 115, 453 [\[\]](#)
- Liu, W.-M., Chen, W.-C., Wang, B., & Han, Z. W. 2010, *A&A*, 523, A3 [\[\]](#)
- McClelland, C. M., et al. 2010, *ApJ*, 720, 704 [\[\]](#)
- McCully, C., et al. 2014a, *Nature*, 512, 54 [\[\]](#)
- . 2014b, *ApJ*, 786, 134 [\[\]](#)
- Miller, J. S., & Stone, R. P. S. 1993, *Lick Obs. Tech. Rep.* 66 (Santa Cruz: Lick Obs.) [\[\]](#)
- Nakano, S., & Itagaki, K. 2014, *CBET*, 4011 [\[\]](#)
- Narayan, G., et al. 2011, *ApJ*, 731, L11+ [\[\]](#)
- Ochner, P., Tomasella, L., Benetti, S., Cappellaro, E., Elias-Rosa, N., Pastorello, A., & Turatto, M. 2014, *The Astronomer’s Telegram*, 6648, 1 [\[\]](#)
- Pilyugin, L. S., Grebel, E. K., & Kniazev, A. Y. 2014, *AJ*, 147, 131 [\[\]](#)
- Schoeniger, F., & Sofue, Y. 1997, *A&A*, 323, 14 [\[\]](#)
- Shara, M. M., Bibby, J. L., Zurek, D., Crowther, P. A., Moffat, A. F. J., & Drissen, L. 2013, *AJ*, 146, 162 [\[\]](#)
- Silverman, J. M., et al. 2012, *MNRAS*, 425, 1789 [\[\]](#)
- Stritzinger, M. D., et al. 2014a, *A&A*, 561, A146 [\[\]](#)
- . 2014b, *ArXiv:1408.1093* [\[\]](#)
- Valenti, S., et al. 2009, *Nature*, 459, 674 [\[\]](#)
- Wade, R. A., & Horne, K. 1988, *ApJ*, 324, 411 [\[\]](#)
- White, C. J., et al. 2014, *ArXiv e-prints*, 1405.7409 [\[\]](#)
- Woudt, P. A., et al. 2009, *ApJ*, 706, 738 [\[\]](#)